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Software design for wireless sensor-based site-specific irrigation

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ABSTRACT

In-field sensor-based site-specific irrigation management is of benefit to producers for efficient water management. Integration of the decision making process with the controls is a viable option for determining when and where to irrigate, and how much water to apply. This research presents the design of decision support software and its integration with an in-field wireless sensor network (WSN) to implement site-specific sprinkler irrigation control via Bluetooth wireless communication. Wireless in-field sensing and control (WISC) software was designed by four major design factors that provide real-time monitoring and control of both inputs (field data) and outputs (sprinkler controls) by simple click-and-play menu using graphical user interface (GUI), and optimized to adapt changes of crop design, irrigation pattern, and field location. The WISC software provides remote access to in-field micrometeorological information from the distributed WSN and variable-rate irrigation control. An algorithm for nozzle sequencing was developed to stagger nozzle-on operations so as evenly distributed over the 60-s cycle. Sensor-based closed-loop irrigation was highly correlated to catch can water with $r^2 = 0.98$.

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1. Introduction

Efficient water management plays an important role in irrigated agricultural cropping systems. Many areas of agricultural fields are effectively over- or under-irrigated due to spatial variability in water infiltration and runoff of rainfall and irrigation, crop water use and irrigation depth. Under-irrigated areas are subject to water stress, resulting in production loss, while over-irrigated areas suffer from plant disease and nutrient leaching. A wireless sensor-based irrigation control system is a potential solution to optimize water management by remotely accessing in-field soil water conditions and site-specifically controlling irrigation sprinklers. The system requires seamless integration of the system input and output components, and software design for decision support and monitoring.

Sensor-based irrigation systems have been studied for many applications (Stone et al., 1985; Jacobson et al., 1989; Zazueta and Smajstrla, 1992; Meron et al., 1995; Testezlaf et al., 1997). Stone et al. (1985) presented a computer-based monitoring system for continuous measurements of soil water potential. Zazueta and Smajstrla (1992) compared indirect estimates with direct measurement of soil moisture. Meron et al. (1995) used a control system for apple tree irrigation management using tensiometers. Testezlaf et al. (1997) used an automated irrigation control system for management of greenhouse container plants.

A well-designed irrigation system is an essential requirement for a profitable and environmental friendly irrigation (Abreu and Pereira, 2002). Wireless radio frequency technology has provided opportunities to deploy wireless data communication in agricultural systems (Oksanen et al., 2004; Zhang, 2004; Lee et al., 2002). Software design for automated irrigation control has been studied by Abreu and Pereira (2002). They designed and simulated solid-set sprinkler irrigation systems by using ISADIM software that allowed to the design of a simplified layout of the irrigation system. However, their software provided limited control due to the lack of feedback in-field sensors.

An automated irrigation system was proposed for remote in-field sensing and variable-rate irrigation control (Kim et al., 2008). The objective of this paper is to describe a user-friendly software design for decision support and monitoring of wireless sensor-based site-specific irrigation system.

A schematic flowchart of an automated irrigation system for variable-rate irrigation is illustrated in Fig. 1. The system consists of machine conversion, localization, and mission planning. The first requirement is to convert a self-propelled irrigation machine from a conventional mechanical and hydraulic system to an electronically controllable system for individual sprinkler head control. Then, it is necessary to be able to continuously monitor the geographic location of the irrigation machine by a self-positioning system. Once the machine is controllable and accessible to its navigation, mission planning must decide when to irrigate and how much water each sprinkler head should apply at each location. This decision support process updates watering instructions according to the cart location and field soil water conditions monitored from sensors distributed

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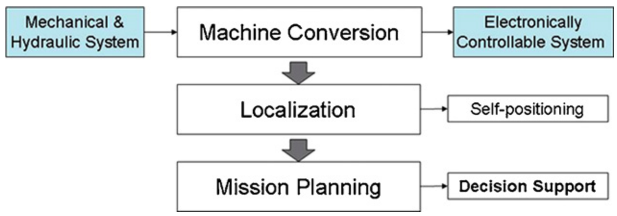

Fig. 1. Schematic flowchart of an automated site-specific sprinkler irrigation system for variable-rate irrigation.

across the field, and sends control signals to a nozzle controller at the irrigation machine.

2. Wireless sensor network (WSN)

A distributed WSN was developed for real-time in-field soil water content sensing (Kim et al., 2008). The network consisted of five sensing stations and a weather station. Each of the sensing stations contained a data logger (CR10, Campbell Scientific Inc., Logan, UT), two soil water reflectometers (CS616, Campbell Scientific Inc., Logan, UT) horizontally at the 30-cm and 61-cm soil depths each, and a soil temperature sensor (107, Campbell Scientific Inc., Logan, UT) at the 15-cm soil depth. The weather station measured precipitation, air temperature, relative humidity, wind speed, wind direction, and solar radiation. Sensors at the in-field sensing and weather stations were scanned every 10 s, and data were stored and wirelessly transmitted every 15 min via a Bluetooth radio transmitter (SD202, Initium Co., Korea) back to a base computer at a receiver (MSP-102a, Initium Co., Korea). All components at each station are self-powered by a 12-V battery that is recharged by a solar panel (SX5, Solarex, Sacramento, CA). The design for power management and wireless communication for the WSN was detailed by Kim et al. (2008).

The wireless sensor network was configured via transmission control protocol (TCP)/internet protocol (IP) to create a virtual serial network. The Bluetooth master at a base station operates as a TCP server, while other seven Bluetooth slaves are registered into TCP data ports. The server receives data from all seven in-field sensor clients and sends the data to the base computer via Ethernet. A serial emulator provides virtual COM ports and redirects to TCP socket connection (Fig. 2).

2.1. Machine conversion

A conventional irrigation machine needs conversion to adapt the in-field sensor-based variable-rate irrigation control. The machine used in the study was a ditch-feed, self-propelled linear-move irrigation system (Valmont Industries, Inc., Valley, NE) equipped with two different sprinkler application methods: mid-elevation spray application (MESA) and low energy precision application (LEPA) (Evans and Iversen, 2005). The irrigation system had six towers including the generator/pump/control cart located at the north end of the system. The machine moved at about 2 m/min at the 100% speed setting.

The machine was converted to make sprinkler nozzles electronically and individually controllable by attaching a programmable logic controller (PLC), solenoids, air valves, GPS, and radio transmitter. The PLC (S7-226, Siemens, Johnson City, TN) was mounted on a main cart and activated electric solenoids (U8325B1V, ASCO, Florham Park, NJ) to control 30 banks (15 for MESA banks and 15 for LEPA banks) of sprinklers via diaphragm valves (205, Bermad Inc., Anaheim, CA). The signal interface and software design for the PLC were detailed by Kim et al. (2008). The PLC updates the GPS position of the irrigation machine every second from a WAAS-enabled differential GPS (17HVS, Garmin, Olathe, KS) and wirelessly transmits the machine position to the base station via a Bluetooth radio transmitter. With feedback of in-field soil water conditions and the irrigation machine positions, the base station makes a real-time decision for site-specific irrigation and wirelessly sends individual sprinkler control signals to the PLC with a complete cycle of closed-loop control within a second via Bluetooth receiver.

2.2. Cost of WSN

The selection of the Bluetooth wireless system was based on communication range, data rate, and cost and intended to accommodate existing devices with plug-and-play type of wireless modules. The total cost of Bluetooth wireless modules used

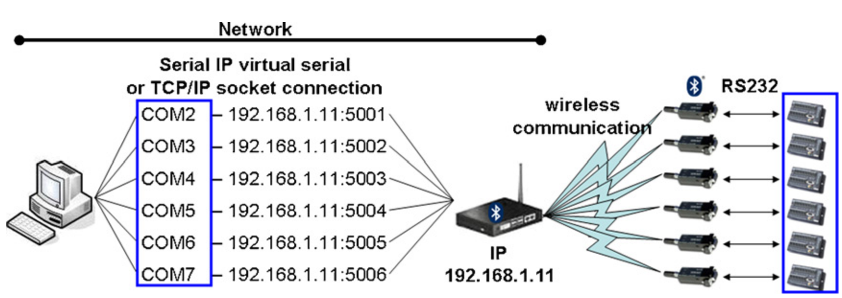

Fig. 2. Virtual serial network. The receiver is configured as a multi-serial Bluetooth server and each Bluetooth device has virtual COM ports and redirected to TCP socket connection.

Table 1
System cost for in-field wireless sensor network with a sensing station.

	Equipment	Unit price	Qt.	Total price
Wireless modules	Bluetooth transmitter (SD202)	$108	7	$756
	Bluetooth receiver (MSP-101a)	$425	1	$425
Sensing station	Soil moisture sensor (CS625)	$150	2	$300
	Soil temperature sensor (109-L)	$70	1	$70
	Data logger (CR200)	$390	1	$390
	Battery (YUASA NP7-12)	$13	1	$13
	Solar panel (SX5)	$90	1	$90
	Sum	$1246		$2044

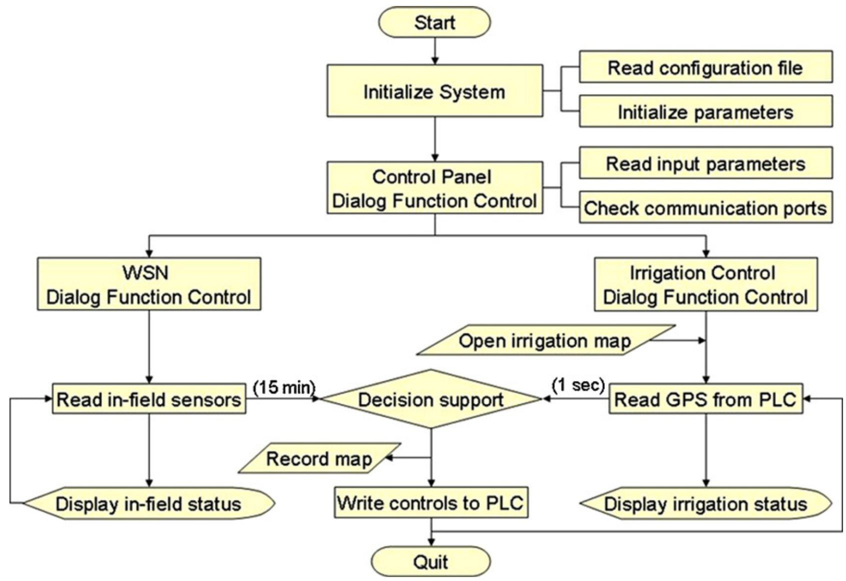

Fig. 3. Algorithm flowchart of WISC Software for sensor-based site-specific irrigation stations that is updated every 15 min.

for in-field WSN was approximately $1200 for seven transmitters (five sensing, one weather, and one PLC control station) and one receiver (base station) as shown in Table 1. The cost of sensing and weather station depends on how many and which sensors are used at how many stations. A sensing station similar to what we used in this study costs approximately $800 for two soil moisture sensors, a soil temperature sensor, data logger, battery, and solar panel (Table 1).

3. Software design factors

There are many design choices to implement the closed-loop irrigation system. The design criterion of our software platform was how easy and efficiently end-users can use the software for comprehensive automation of their irrigation field. The growers want to see on the computer monitor at home the status of soil moisture at various locations including weather information and monitor irrigation operation by pulling up a map that sees how much water at where to apply or creating a new irrigation map by simple click-and-drag. During the irrigation, they may also want to see the current location of their irrigation machine, how far it went, and when it will reach the destination. If a rain shower passes over the field, they should be hoping the software to automatically adjust the amount of water being applied.

To meet all grower's concerns and requirements, user-friendly software was developed for real-time wireless in-field sensing and control (WISC). The software was Windows-based custom software and coded as a Win32 application using Microsoft Visual C++.Net (ver. 7.1). The WISC software was able to read the GPS data through the PLC and send control signals back to the PLC for individual sprinkler control after completing a decision making process.

The algorithm flowchart of the WISC software is shown in Fig. 3. The software was updated from version 1.0 (Kim et al., 2006) to integrate the feedback of wireless sensor network into the decision making process. The decision support process is based on feedback of in-field data every 15 min and GPS updates of the location of the machine control cart every second. The actual amount of water applied to each plot is calculated based on the cycle ratios, recorded GPS-referenced times and locations during the irrigation operation and written to a file for reference.

The WISC software consists of four main design factors: control panel for hardware interface, graphical monitoring for in-field WSN, irrigation control and monitoring, and nozzle sequencing. Each design factor featured self-explanatory, click-and-play menu using graphical user interface (GUI) including an optional simulation function. The software was further optimized to adapt changes of crop design, irrigation pattern, and field location.

3.1. Control panel

A control panel dialog was created to configure data interface for the irrigation control system. A GPS clock was corrected from Greenwich mean time (GMT) to a local time based on a time zone, and −6 was added to represent a U.S. Mountain time with daylight saving (Fig. 4). The GPS offset was set to zero for both *x*- (east) and *y*- (north) axes, as the GPS was mounted on the middle of a main linear control cart with sprinkler nozzles aligned along a longitude line. The status of communication ports for the GPS and PLC are automatically detected on the software initiation, and corresponding serial port numbers are displayed (Fig. 4). A pushbutton 'Irrigation Control' in Fig. 4 opens a real-time GPS-based irrigation control and monitoring dialog. During the irrigation operation, PLC communication connectivity is alerted every second after a complete cycle of data processing by a short beep sound, ranging from 0 (silent) to 10 (loudest).

The 15-min update rate of the WSN data is based on a computer clock, while 60-s duty cycle of irrigation operation is based on a GPS clock. To avoid time mismatch between sensor feedback input and irrigation control output data in decision making, it is necessary to synchronize a computer clock with a GPS clock and convert to a correct local time by clicking a pushbutton of 'Synch PC clock with GPS' (Fig. 4). All data are recorded during the irrigation operation and saved to a file named 'PLC_mmdd.csv', where 'PLC' is a default filename and 'mm' and 'dd' are the current month and day, respectively. Each data string contains actual amount of water applied on each plot with GPS data.

3.2. Remote monitoring of WSN

A WSN dialog was added to provide a graphical display of the sensory data and to integrate in-field sensor feedback with an irrigation controller. There were five sensor stations numbered from 1 to 5 and a weather station numbered 6. Boxes under 'Station ID' on a WSN are checked as default to show all six stations and can be

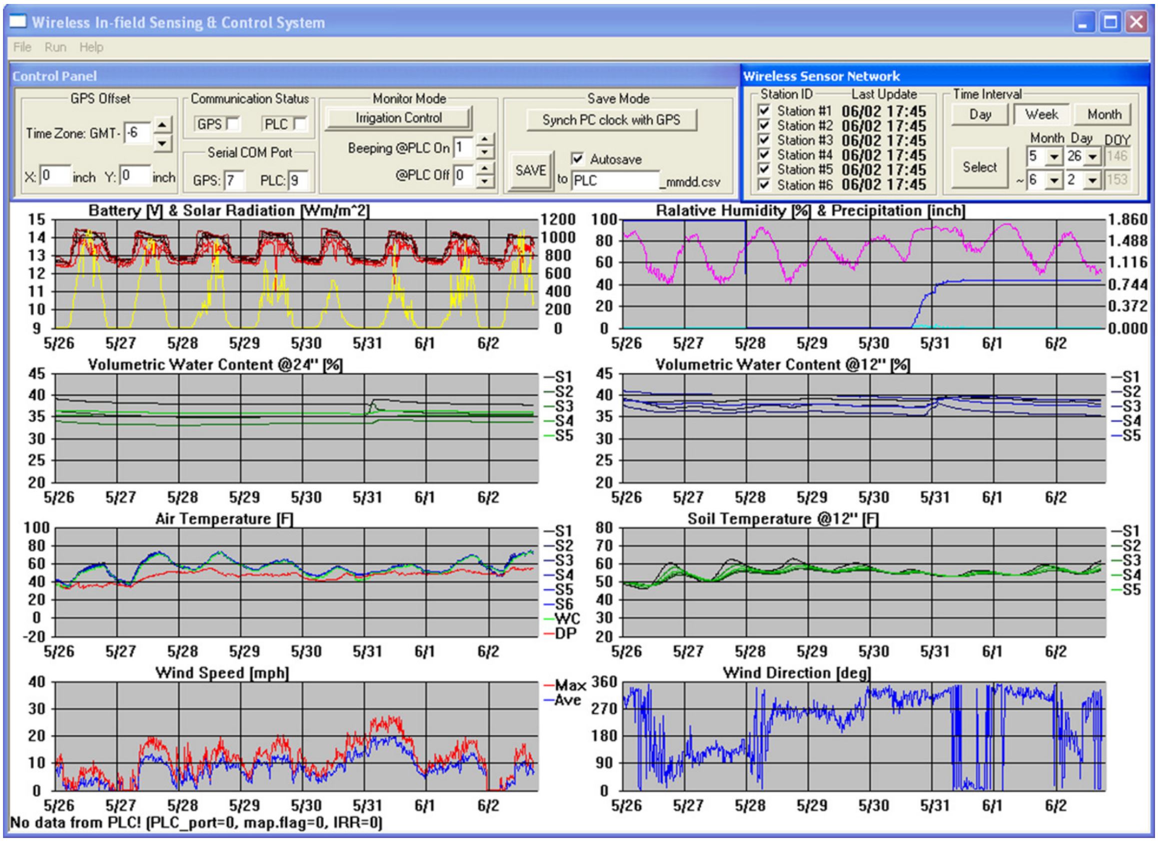

Fig. 4. Graphical display of in-field sensor data received from wireless sensor network.

unchecked to see individual station data (Fig. 4). Time updates at each station are displayed next to the station list and used to check the status of radio communication and data transmissions. Weekly display of graphs was selected as default and can be changed to daily, monthly, or manual selection based on date or day of year (DOY), as shown in Fig. 4.

3.3. Real-time control of variable-rate irrigation (VRI)

A GPS-based irrigation control dialog was created to provide interactive real-time control and monitoring of the site-specific irrigation operation. The dialog displays a background image of experimental plots and interactive control menu for wireless irrigation control. The image shows a base station in the research center on the left hand side and experimental plots 700 m away on the right hand side (Fig. 5). The irrigation plot image can be zoomed by selecting the 'IN' or 'OUT' button on at the top of the plot image. An irrigation map is selected from the 'OPEN' button and displayed over the plot image by clicking the 'Irrigation Map' button. Fig. 5 shows an example map of 30 sprinkler banks (15 for MESA in blue and 15 for LEPA in green).

The dialog allows selection of irrigation plots on crop menu buttons in 'Crops' at the top of the plot image. Plots to irrigate are selected based on crop types (sugar beet, barley, potato, wheat, etc.). Fig. 5 shows a total of 480 subplots (32 × 15) for variable-rate irrigation. Each subplot was color coded according to irrigation sprinkler types (light blue for MESA and light green for LEPA). User can define an irrigation type by clicking each subplot to toggle sprinkler types (MESA 100%, LEPA 100%, or 0% no water) and the amount of water application of each subplot from 0 to 100% with 1% increment by click-and-dragging each slide bar in 'Nozzle Duty Cycle [%]' on the right hand side of Fig. 5, changing color intensity accordingly (more water in darker color). A modified irrigation map can be stored by selecting the 'SAVE' button to a map file with information of grid, crop locations, sprinkler type and percentage water amount on each subplots.

The software receives GPS locations of the cart from the PLC and sends individual control signals for all sprinkler nozzle banks every second automatically on request after processing in-field sensory data for decision making. It also allows manual control by disabling 'Auto Nozzle Control' and selecting each span checkbox in 'Real-Time Nozzle Control' at the right top corner of Fig. 5. The 'Toggle MESA/LEPA' checkbox allows toggling MESA and LEPA when selecting either one, which prevents redundant irrigation on the same sprinkler banks. The decision rule base for variable-rate irrigation controls the amount of water applied by adjusting the duty cycle of each sprinkler bank in a period of 60 s. For instance, 50% water application turns the nozzle on for 30 s and off for 30 s. When the irrigation cart moves across a plot boundary, irrigation data are recorded during the irrigation operation to a file containing each string name labeled with a local time stamp to the nearest millisecond, plot number, GMT time, longitude, latitude, and percentage of water actually applied on each plot row. The 'Simulation' button offers an option to simulate the variable-rate irrigation operation on a selected irrigation map with a slide bar of speed control.

3.4. Nozzle sequencing for VRI

The variable-rate irrigation is implemented by controlling nozzle on and off, and thus the sequence of nozzle operations must be carefully assigned to avoid system damage from high hydraulic pressure. Based on an assumption of 50% of total sprinkler banks as a minimum number of nozzle-on banks for safe hydraulic operation, the nozzle operation requires a staggering process to distribute

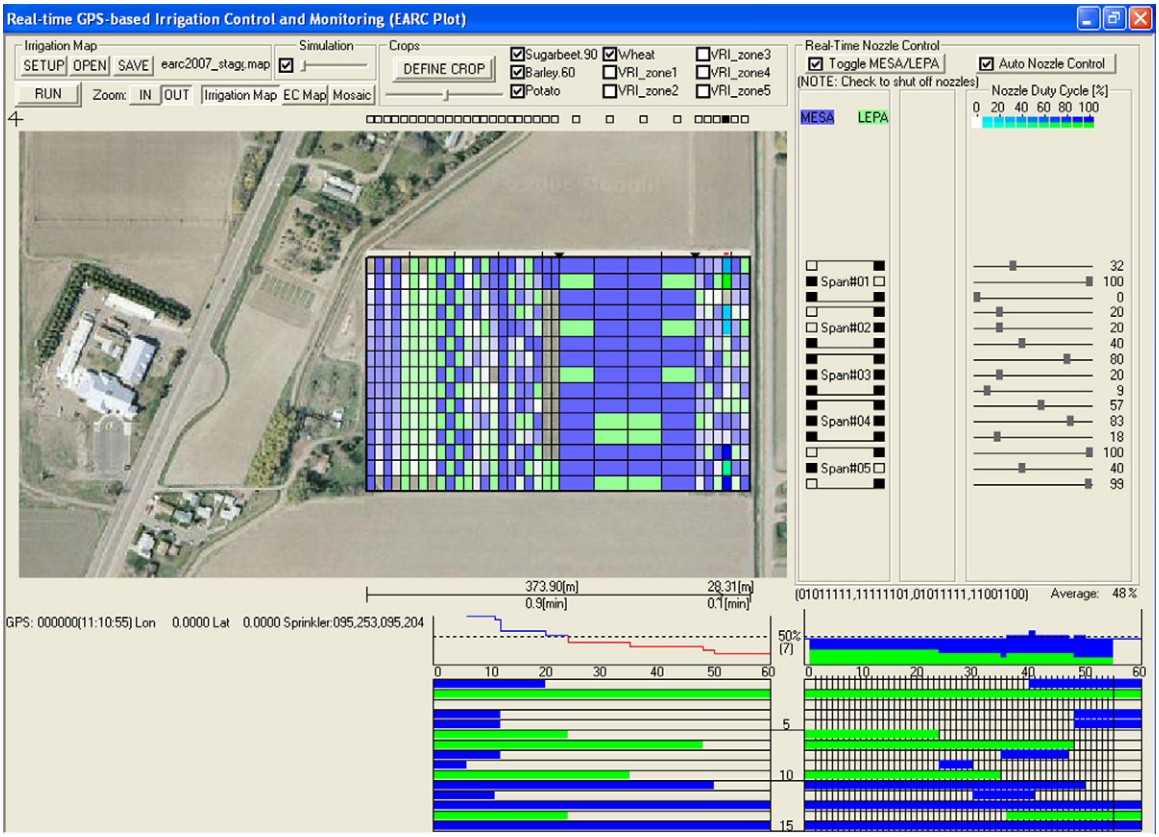

Fig. 5. GPS-based irrigation control dialog for real-time wireless irrigation control and monitoring, showing the sequence of nozzle-on operation at the bottom: without staggering (left, unstable below 50%), with staggering (right, stable all above 50%).

the nozzle-on operations evenly during 60-s duty cycle. Two histogram at the bottom of Fig. 5 display the status of total nozzle-on operations by 15-horizontal timeslot bars whose length indicates nozzle-on watering duration out of 60-s full length (100% watering) in two different sprinkler types: MESA in blue and LEPA in green. The graph above each histogram illustrates the cumulative timeslot status of total nozzle-on banks. The left histogram shows operation without staggering in which all 15 sprinkler banks start the nozzle-on operation at the beginning of the 60-s cycle and result in an unsafe (upper graph in red line in Fig. 5) system after 24 s, because the total number of the nozzle-on banks becomes less than the 50% (7 banks) of the entire sprinkler banks (15 banks). The right histogram shows the staggered timeslots that were distributed to achieve the total number of nozzle-on banks above the 50% all the time across the 60-s cycle.

An algorithm was developed to implement the staggering process with 15 timeslots for each of nozzle bank operations, as shown in Fig. 6. The goal of the staggering algorithm is to maintain the total number of nozzle-on banks more than a half of the entire sprinkler banks by rearranging nozzle-on timeslots (horizontal bars) within 60-s duty cycle. When a time (t) during the 60-s cycle is initialized to zero, the timeslots are sorted. Seven longest timeslots are searched and located to start at $t = 0$, while the rest of eight shortest timeslots are located to end at $t = 60$. If the total number of nozzle-on banks becomes less than 7, then an unused shortest timeslot is located to start at the time (t_0) the previous timeslot ends until the total number is summed to 7. As time goes, the duration of the seven longest timeslots ends in the order of their timeslot length. On the right histogram in Fig. 5, for instance, the bank# 6 ends the nozzle-on duration at $t = 24$ in earliest among the seven longest timeslots (banks# 2, 6, 7, 10, 11, 13, and 15), which causes the total number of nozzle-on banks to 6 (less than 50%). In order to bring the number back to 7, the bank# 9 is selected as an unused shortest timeslot among the rest of eight shortest timeslots (banks# 1, 3, 4, 5, 8, 9, 12, and 14) and placed to start at $t = 24$. This process repeats until the time reaches to the end of the cycle at $t = 60$ and restarts a staggering cycle.

4. Software optimization

Seasonal changes of irrigation patterns and different irrigation machines at different locations constrain the global use of the irrigation software. To overcome such constraint, this study was performed to optimize the irrigation software for the unconstrained use of variable-rate application via user-friendly graphical user interface.

4.1. Scalable plot design

The plot layout (e.g. spacing) of individual irrigation plots can be varied over season and must be externally user-defined by irrigation software. The WISC software was optimized to adapt the changes of the field layout by making boundary lines of subplots adjustable so that each boundary line can be adjusted by click-and-drag and referring to a display of GPS location. Each boundary line can be landmarked for user reference, and its mark (inverted solid triangle in Fig. 5) is toggled on/off by clicking the top of the boundary line. All changes of grid and plot layout are included in each irrigation map, when it is saved to a map file.

4.2. Re-locatable field design

The different irrigation fields at different locations changes the field size and irrigation pattern and must be adapted by irrigation

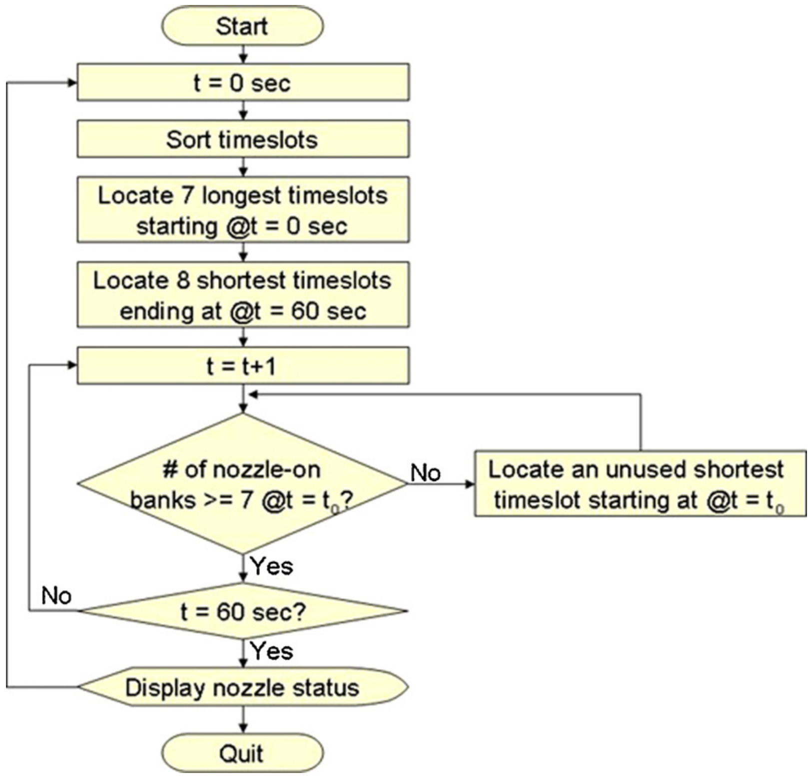

Fig. 6. Schematic flowchart of nozzle sequencing for variable-rate irrigation.

software. The GPS location of the field is reconfigured by selecting the 'SETUP' button in Fig. 5, where the latitude and longitude of four boundary corners of the field are edited. The button also provides reconfiguration of field layout (e.g. size and numbers) of the irrigation plots, where the field grid is scalable up to 100 (column) × 50 (row) with maximum 5 sprinkler banks per span to adapt different irrigation. All real-world GPS coordinates are converted to image coordinates to fit in a screen size and register pixels to a real-world coordinates. According to the field geographical layout, the field orientation mark (4) is displayed on the left top corner of the irrigation map, and navigation information is displayed for distance and time traveled/to travel with a status arrow of heading direction at the bottom of the irrigation map in Fig. 5.

4.3. Reconfigurable crop design

The crops are changed over the season, and the field needs to be reconfigured to define which crop is located at where. The 'DEFINE CROP' button on the top of the irrigation map in Fig. 5 allows a user to redefine the type of crop and reassign each individual subplot to a different crop by selecting a crop and clicking each subplot to include/exclude, which toggles red-boxed/no-boxed, respectively. Once crops are all defined, selecting a crop will include in irrigation operation only subplots assigned in the define mode to the crop.

5. Experiment and results

The WISC software was tested for in-field wireless sensor-based closed-loop irrigation control during the 2007 growing season under a linear-move irrigation system on a field planted to malting-barley at the Eastern Agricultural Research Center of Montana State University in Sidney, MT. Five in-field sensing stations were installed at five different soil zones labeled in descending order of soil electrical conductivity, while an in-field weather station was mounted on the linear irrigation cart. The manually selected travel speed of the linear-move sprinkler system determines the maximum application depth. The amount of water applied was determined by the deficit of the current soil moisture status from

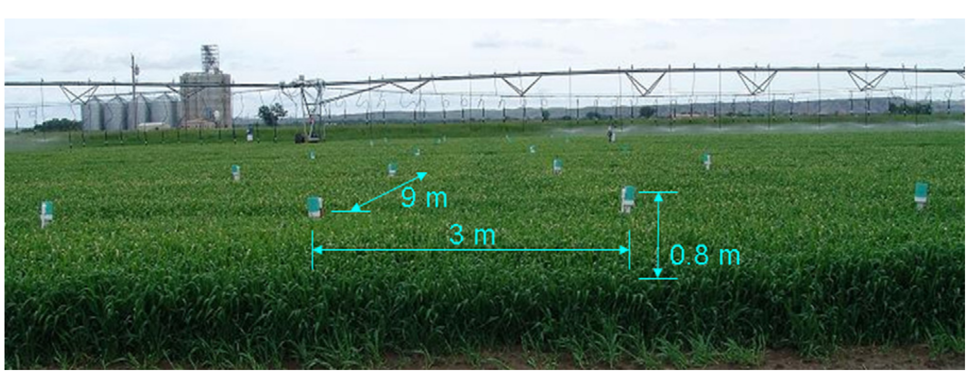

Fig. 7. Experimental setup on malting-barley with four catch cans installed at each of five soil zones with 3 m apart and 0.8 high.

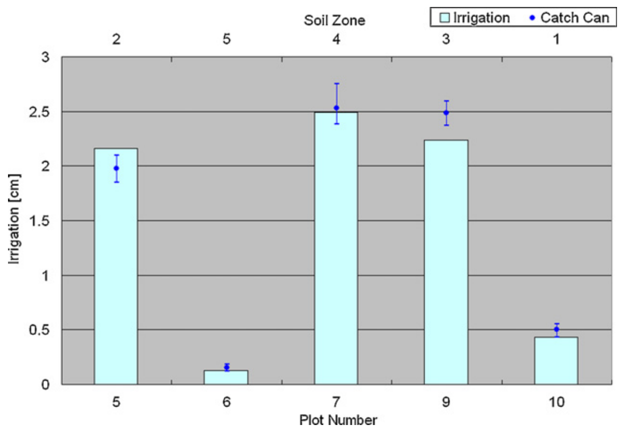

Fig. 8. Water collected by catch cans compared to irrigation amount at five soil zones.

the upper limit value of the range of each sensor to apply a percentage of maximum. Sensor calibration and decision making process are detailed in Kim et al. (2009).

The amount of water to apply at each of VRI plots is updated every 15 min by in-field soil water feedback from all five soil zones. The soil water status at each sensor station represents all rest of area that belongs to the same soil zone and is distributed across the VRI plots. Catch cans were installed across a strip that contained all five soil zones and aligned between two MESA sprinkler heads (Fig. 7). The cans catch water only from MESA nozzles, since LEPA nozzles drop water below catch cans' height. Fig. 8 shows catch can data collected on August 16, 2007 and compared to irrigation amount that was determined by decision making process, ranging 0.1–2.5 cm water over the five soil zones. They were correlated to the irrigated amount with $r^2 = 0.98$ with average 0.08 cm of more catch can water under the wind drift of average 10 km/h at 18° wind direction.

6. Conclusions

A wireless sensor-based site-specific irrigation system requires a seamless integration of in-field wireless sensor network and closed-loop control of sprinkler nozzles and must be easily used and simply managed by end-users (growers) via user-friendly software. A real-time wireless in-field sensing and control software was developed to integrate a site-specific irrigation controller with in-field data feedback and support the decision making and real-time monitoring of irrigation operations via Bluetooth wireless radio communication. This paper provided to readers details of software design choices with design factors and optimizations for unconstrained global use. Each design factor featured self-explanatory, click-and-play menu using graphical user interface including an optional simulation function. An algorithm for nozzle sequencing was developed to minimize hydraulic pressure surges by staggering and uniformly distributing the nozzle-on timeslots during 60-s duty cycle. The system successfully enabled real-time remote access to the field conditions and feedback control for site-specific irrigation with high correlation of $r^2 = 0.98$ to water collected by catch cans. The benefit of software design extends to adapt automated site-specific fertilizer or chemical applications.

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